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Design and Manufacture of Structurally Efficient Tapered Struts

Jebediah W. Brewster

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December 2009

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1.0 INTRODUCTION

Lockheed Martin Space Systems Company (LMSSC) has designed and built numerous composite strut structures for a variety of aerospace applications, including several NASA and DoD Spacecraft missions. Among these components are spacecraft truss structures for Magellan, Stardust, MRO, Phoenix, Milstar, Special Programs, X-33 and Orion W-truss. Typically, each of these truss structures included constant diameter strut elements.

This task, “Design and Manufacture of Structurally Efficient Tapered Struts”, offers a unique opportunity to further develop and enhance the aerospace industry’s ability to manufacture lighter and stiffer struts for future NASA missions, lunar landers, and lunar habitats.

Our manufacturing task successfully accomplished its objective to manufacture a structurally efficient tapered composite strut for the Altair lunar lander. To accomplish this objective, the following key efforts were undertaken:

- 1) Analytical stress analysis and design optimization:
 - a. Structural Analysis Code For Stress Analysis
 - i. ABAQUS
 - b. Optimization Codes For Tapered Strut Sizing
 - i. Mathcad optimization code created for tapered strut optimization
 - ii. Mathcad program was converted into fortran. It was interfaced with a more robust optimization code developed by Vanderplaats Research & Development called VisualScript and VisualDOC
- 2) Weight optimization results showed a system approach was required to optimize a tapered strut:
 - a. Fitting needed to be sized to take the required loads
 - b. Fitting design influenced end interface diameters of tapered strut
 - c. Node concept influenced end fitting design
 - d. Node, fitting, tapered strut were optimized as a system, not as stand alone components
 - e. End fitting design concept completed
 - f. Node design concept completed
- 3) San Diego Composites (SDC) successfully manufactured a subscale tapered demo strut to design requirements:
 - a. Maximum center ID to minimum end ID silicon bladder removal demonstrated
 - b. $\pm 45^\circ$ fabric layup from varying diameters to constant diameters demonstrated
 - c. 0° ply layup over contour changes demonstrated
 - d. Processes used easily carries over to full sized struts

These accomplished tasks demonstrated all aspects of project management, technical analysis, and design as well as the combination of practical manufacturing aspects into the optimal tapered composite strut design for successful production.

The successful completion of all required tasks plus the additional efforts of analyzing the node-end fitting-tapered strut system for a weight optimized product demonstrates LMSSC's ability to deliver a practical and affordable optimal design solution.

2.0 TECHNICAL ACCOMPLISHMENTS

2.1 Analytical Trade Studies and Design Optimization

An analytical trade study was conducted to design structurally efficient composite struts with the geometries and loading conditions for the two strut design cases (case 1 and case 2) listed in Table 2-1.

**Table 2-1 Strut Dimensions and Design Loads.
Limit Load Requirements at Room Temperature.**

Case	Length	Load	Boundary conditions
1	135 inches	Axial compression, 44,000 lb	pinned on both ends
2	127 inches	Axial compression, 110,000 lb	pinned on both ends

Case 2 was chosen as the demonstration strut as it had the highest compression load case and is the greatest engineering challenge for determining a mass optimized solution and proving manufacturability.

LMSSC used past experience to derive more extensive requirements that are realistic for a space environment. Based on judgment and experience we “derived” the following additional requirements:

- 1) Axial tension load of 45,000 lbs. Boundary condition is pinned on both ends.
- 2) High ramp-up compression load case (potential impact load).
- 3) Temperature operating range of -150°F to +250°F (temperature range can be increased if required).

Figure 2-1 shows the steps involved in the optimization process, including input variables, the potential failure criteria and the load requirements. An iterative process optimization established the geometry and ply layup for the minimum weight design. While this analytical optimization process provided a structurally efficient design, the final optimal product design included specific considerations from SD Composites for the manufacturing processes. This included ply layup orientations as well as inclusion of fabric plies.

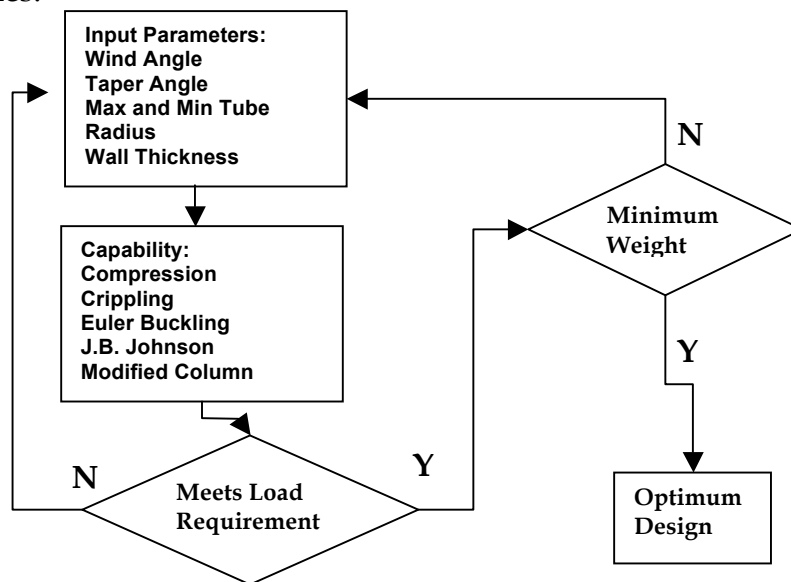


Figure 2-1 Composite Tapered Tube Analysis and Optimization Process

A safety factor of 1.5 and a fitting factor of 1.15 were used for all analysis.

In all analysis, the following failure modes are analyzed:

- Compression
- Crippling
- Euler Buckling (long tapered column)
- J.B. Johnson Buckling (intermediate constant cross section column)
- Modified Column Buckling

Due to LMSSC's extensive database and design experience with the high modulus carbon graphite M55J coupled with HexPly 954-3 cyanate resin, it was chosen for use as our baseline composite material for design optimization. Also, it is desirable to have the tube hoop coefficient of thermal expansion (CTE) greater than or equal to that of the internal titanium fitting. This will make the tube shrink unto the fitting at cold temperatures resulting in improved bondline strength at the worst case cold condition. The optimum design had a 32 ply lay-up ($\pm 45^\circ/0^\circ_9/\pm 45^\circ/0^\circ_5$)_{SYM} with the 0° uni-directional ply thickness of 0.005 in and $\pm 45^\circ$ fabric of 0.010 in. This optimum design includes both stress and manufacturing requirements. Results of the analysis indicate that a weight saving of 61% was achieved over an aluminum truss having the same overall length.

It should be noted that a constant wall thickness was found to be more weight efficient then a variable wall thickness. However, a variable wall thickness (constant area) was taken into consideration to support the use of filament winding manufacturing.

The weight optimized tapered strut was sized by column buckling. It was assumed that the tapered strut was pinned at both ends. The tube length was used for the column length.

The optimized results are given below:

Table 2-2
Weight Results for Optimized Struts

Case	Strut Length/Tube Length	Limit Load	Material System	# of Ply's	Weight lbs
1	135 in 126 in	Axial compression, 44,000 lb	M55J /954-3	20	9.89
2	127 in 118 in	Axial compression, 110,000 lb	M55J /954-3	32	17.69

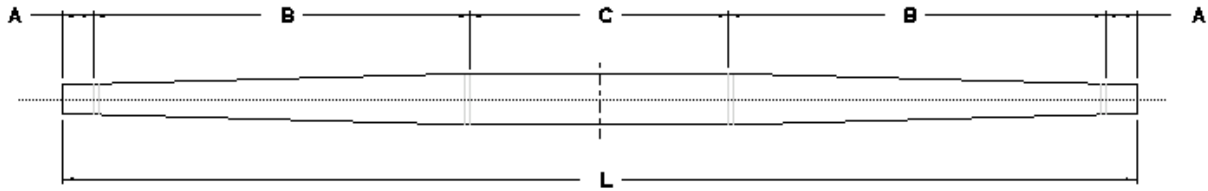
Case 1 Ply Orientation: 20 ply lay-up ($0^\circ_4/\pm 45^\circ/0^\circ_5$)_{SYM}

Case 2 Ply Orientation: 32 ply lay-up ($\pm 45^\circ/0^\circ_9/\pm 45^\circ/0^\circ_5$)_{SYM}

Our initial optimization studies had no center cylindrical section (C) for a true completely tapered strut. Further investigations revealed that having a very small

cylindrical section (C) in the center of the strut and had no weight impact but greatly aided the manufacturing layup process. The optimized dimensions are given below:

Table 2-3 Optimized Struts Dimensions



Case	Tube Max Mean Dia (in)	Tube Min Mean Dia (in)	Taper Angle ϕ (deg)	Tube Length A (in)	Tube Length B (in)	Tube Length C (in)
1	4.87	3.00	0.96	1.12	55.80	12.17
2	5.43	3.18	1.56	3.42	41.31	28.54

A preliminary analysis of the load Case 2 in Table 2.1 was performed in order to provide a top level assessment of the scope and feel for the weights of this tapered strut. It quickly became apparent after this top level assessment that the end fittings could weigh as much as the 127 inch long strut and that the loads thru the end fittings heavily influenced the cylindrical ends portion of the tapered strut in both the diameter and length of the bonded end fitting interface section.

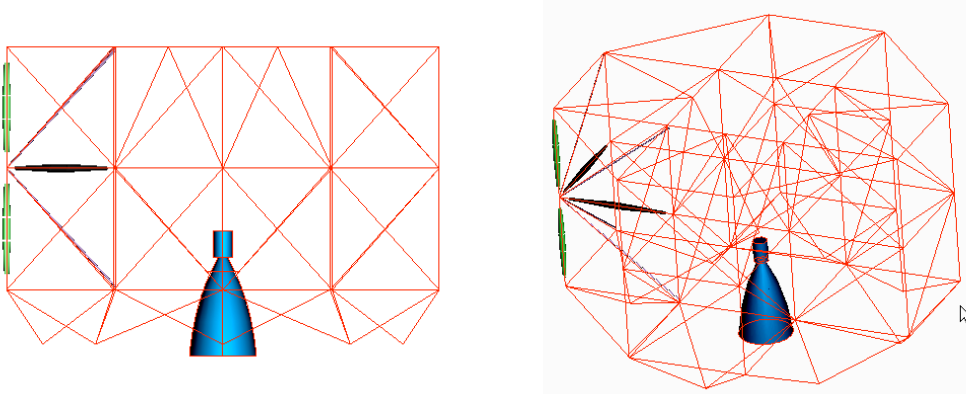
2.1.2 Design Development of Tapered Strut, End Fitting, and Node System

After these early optimization runs on the tapered strut, it became apparent that the total strut system had to be considered in order to optimize the tapered struts to realistic requirements. The 110,000 lbs compression load with 1.50 factor of safety and 1.15 fitting factor created an ultimate load case of 190,000 lbs. Space Systems had never designed a composite strut that could take a compression load of this magnitude. After extrapolating from the successfully tested X33 composite struts database, it became apparent that the adhesively bonded area would require an impractical bondline length. In addition, our derived requirements suggested that the exceptionally high compressive load could be the result of a very fast ramp up load case (impact load). Impact loads are not conducive to a successful bonded joint system. No tension load case was given, but in an actual flight environment, some tension loads would exist so we derived a tension load. Finally, we also derived reasonable cold and hot temperature requirements from our past spacecraft experience for a realistic space environment.

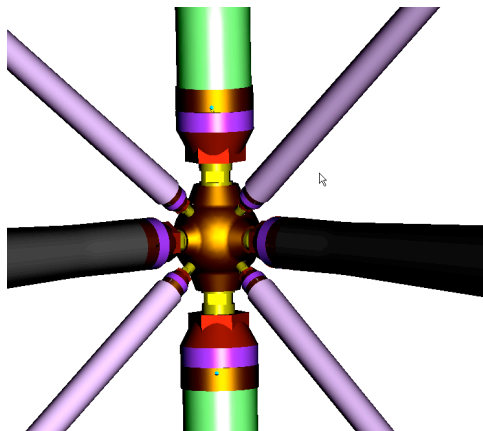
In order for the end fitting to take this exceptionally high compression load with the derived tension load and temperature requirements, a new type of joint had to be

invented. The new designs considered the total system requirements, not only just for the tapered strut, but also for the end fittings and attach nodes. Our approach then became not to just optimize the tapered strut, but to optimize for the total system requirements of the tapered strut, end fittings, and attach nodes for minimum weight.

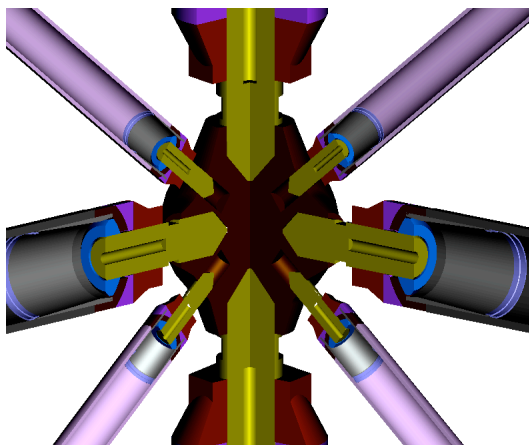
The initial node system design work utilized the NASA DAC1 Altair Lunar Lander ProE model and focused on a typical corner joint.



NASA DAC1 Altair Lunar Lander ProE Strut Centerline Model



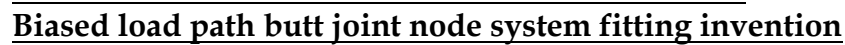
Typical Altair corner node joint system concept.



Corner Cross Section of concept node system. Note conical solid contact interface joints for very high compression load.

The consideration of a typical corner included the main load vertical X-dir compression struts, the horizontal Y-dir compression/tension struts, the cross connection stabilizing struts, and the

A diagram showing a long, tapered green component with a central white longitudinal stripe. The component has yellow and pink end fittings. A double-headed arrow below the component spans its entire length, labeled "Approximate Pin-to-Pin Length".



Title: Biased Dual Load Path Spherical Joint Strut End Fitting



very simple, small node and an end fitting that will utilize a special spherical bearing moment release system. The node concept will be designed and optimized for the number of connections at each node while the end fittings will be designed and optimized to each load case. Our analysis has also shown that for low loaded struts, a tapered strut is not the most optimized system, but instead a constant diameter strut is more effective. Thus for a complex corner joint, there will be tapered and constant diameter strut connections as well as different end fitting diameters and pins. It may be possible to consolidate the load cases into classes of joints and therefore may only have a minimal number of different types of nodes and end fittings for commonality in the manufacturing effort. In addition, our experience gives us insight that the Altair Lunar Lander strut system optimization effort must collectively “load up” all struts evenly to effectively share the load which will then reduce the total system weight of the strut system. This collective optimization may increase the number of different strut configurations but the design impact may only be to change the number of plies for a standard size tapered strut. Thus, a very effective collective evenly loaded strut system may be created only by changing the number of plies applied to each tapered strut. The end fitting butt joint efficiently solved the extremely high compression load engineering challenge. What was more difficult and time consuming, was the design of the end fitting to take the derived tension load. The load path for the tension load is not the same as the load path for the compression load thru the end fitting interface. The derived tension load is also a high load case, but LMSSC had the experience and test data to successfully design and analyze the end fitting for the derived tension load case. Many design and stress iterations were utilized in order to come up with a fitting that had an acceptable bondline stress distribution. The bondline joint solution was determined by Dr. Mark Lajczok, our subject matter expert in this field. The biased load path end fitting joint was successfully designed and analyzed for the extremely high compression load case and the derived high tension load case. Further optimization and weight reduction is possible with more test data.

2.1.3 Bonded Joint Margin Evaluation

The flatwise tensile failure (delamination) of M55J/954-3 is one of the primary failure mechanisms of the bonded joint. The Margin of Safety (M.S.) equation for delamination is given below:

$$M.S. = \frac{1}{\sqrt{R_a^2 + R_s^2}} - 1$$

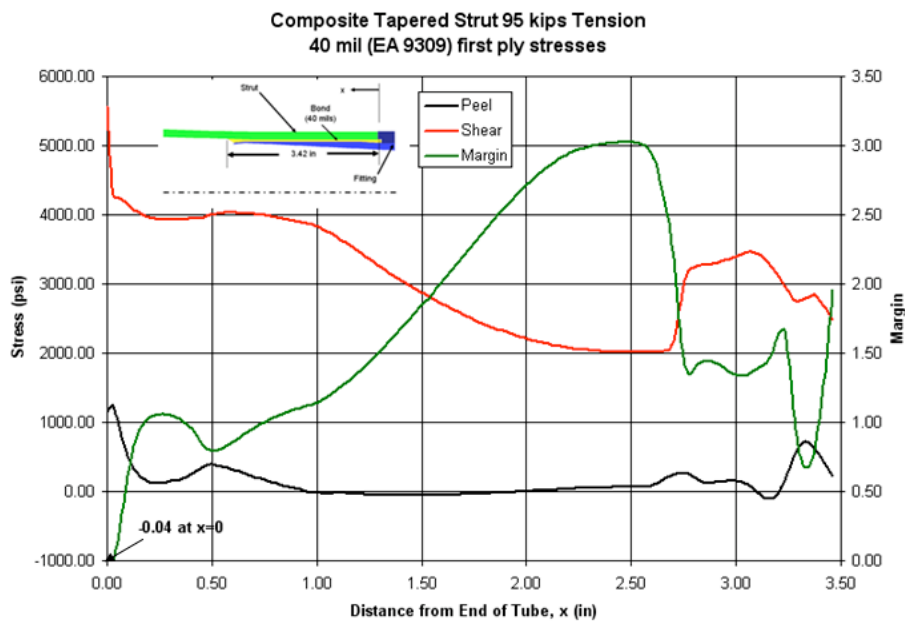
$$\text{for } \sigma_z \geq 0.0 \quad R_a^2 = \left(\frac{\sigma_z}{\sigma_{za}} \right)^2, \quad R_s^2 = \left(\frac{\tau_{xz}^2 + \tau_{yz}^2}{\tau_a^2} \right)$$

$$\text{for } \sigma_z < 0.0 \quad R_a^2 = 0.0, \quad R_s^2 = \left(\frac{\tau_{xz}^2 + \tau_{yz}^2}{(\tau_a + 0.5\sigma_z)^2} \right)$$

where

σ_z = flatwise tension stress
 τ_{xz}, τ_{yz} = interlaminar shear stress
 σ_{za} = flatwise tension strength
 τ_a = interlaminar shear strength

A preliminary assessment of the first ply margin for the tension load case was performed based on the 0° uni-directional ply being the first ply adjacent to the bondline. The adhesive and fitting analyses were allowed to go into the plastic regime. As shown below, the margin at the base of the fitting is slightly negative but we believe successful testing will confirm our conservative analysis results.

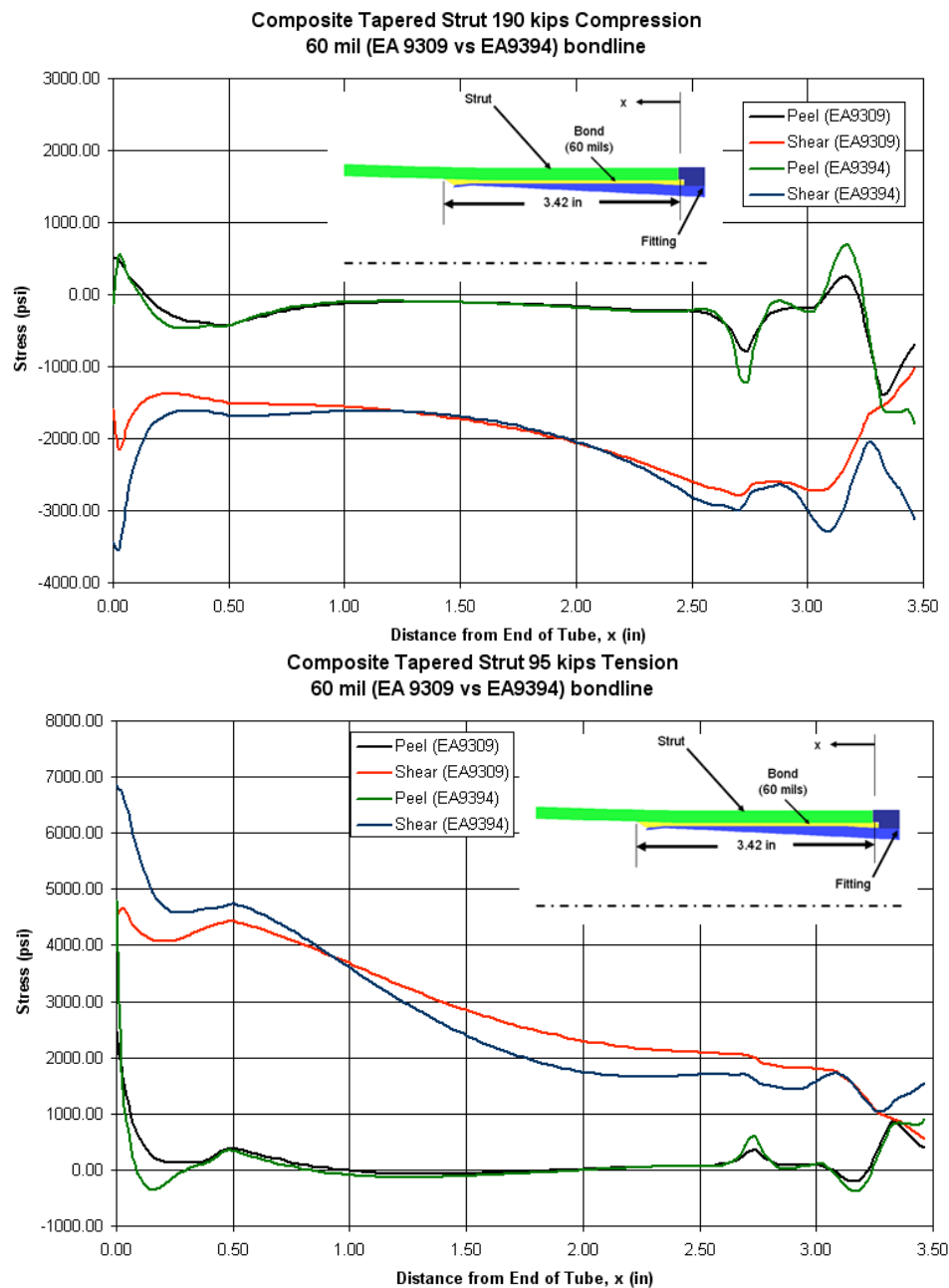


2.1.4 Epoxy Adhesive Evaluation

An investigation into comparing epoxy adhesive EA9394 to EA9309 bondline stress levels revealed that EA9309 was the preferred choice. The properties of both adhesive systems at room temperature are given below:

Properties	EA9394	EA9309
Young's Modulus (Msi)	0.688	0.216
Shear Modulus (Msi)	0.238	0.08
Poisson's ratio	0.447	0.36
Shear Strength (psi)	5815	5240
Yield Strength (psi)	7500	6928
Ultimate Strength (psi)	12900	9076
Elongation (%)	1.66	10

A comparison between EA9394 and EA9309 on the bondline peel (flatwise tensile) and shear stress is presented below for both compressive and tensile loading:



EA9309 was chosen over EA9394 based on the following reasons:

- High Ductility
- Flaw Tolerance due to excellent stress redistribution capability
- High glass-transition temperature after post cure
- Stable thermal cycling characteristics
- Good wetting characteristics
- Reduced Stiffness (reduces bondline stresses)

2.1.5 Composite Evaluation

An investigation into comparing IM-7/5250-4 to M55J/954-3 composite resin systems revealed that M55J/954-3 was the preferred choice. The properties of both composite materials at room temperature are given below:

IM-7/5250-4

LAMINA PROPERTIES

(1 -fiber, 2-transverse)

Temp (°F)	E ₁₁ (Msi)	E ₂₂ (Msi)	G ₁₂ (Msi)	ν_{12}	α_{11} (10 ⁻⁶ /°F)	α_{22} (10 ⁻⁶ /°F)
RT	22.5	1.4	0.90	0.33	-0.12	14.2

M55J/954-3

LAMINA PROPERTIES

(1 -fiber, 2-transverse)

Temp (°F)	E ₁₁ (Msi)	E ₂₂ (Msi)	G ₁₂ (Msi)	ν_{12}	α_{11} (10 ⁻⁶ /°F)	α_{22} (10 ⁻⁶ /°F)
RT	43.45	0.96	0.435	0.15	-0.55	17.7

M55J/954-3 was chosen over IM-7/5250-4 because of its high fiber stiffness.

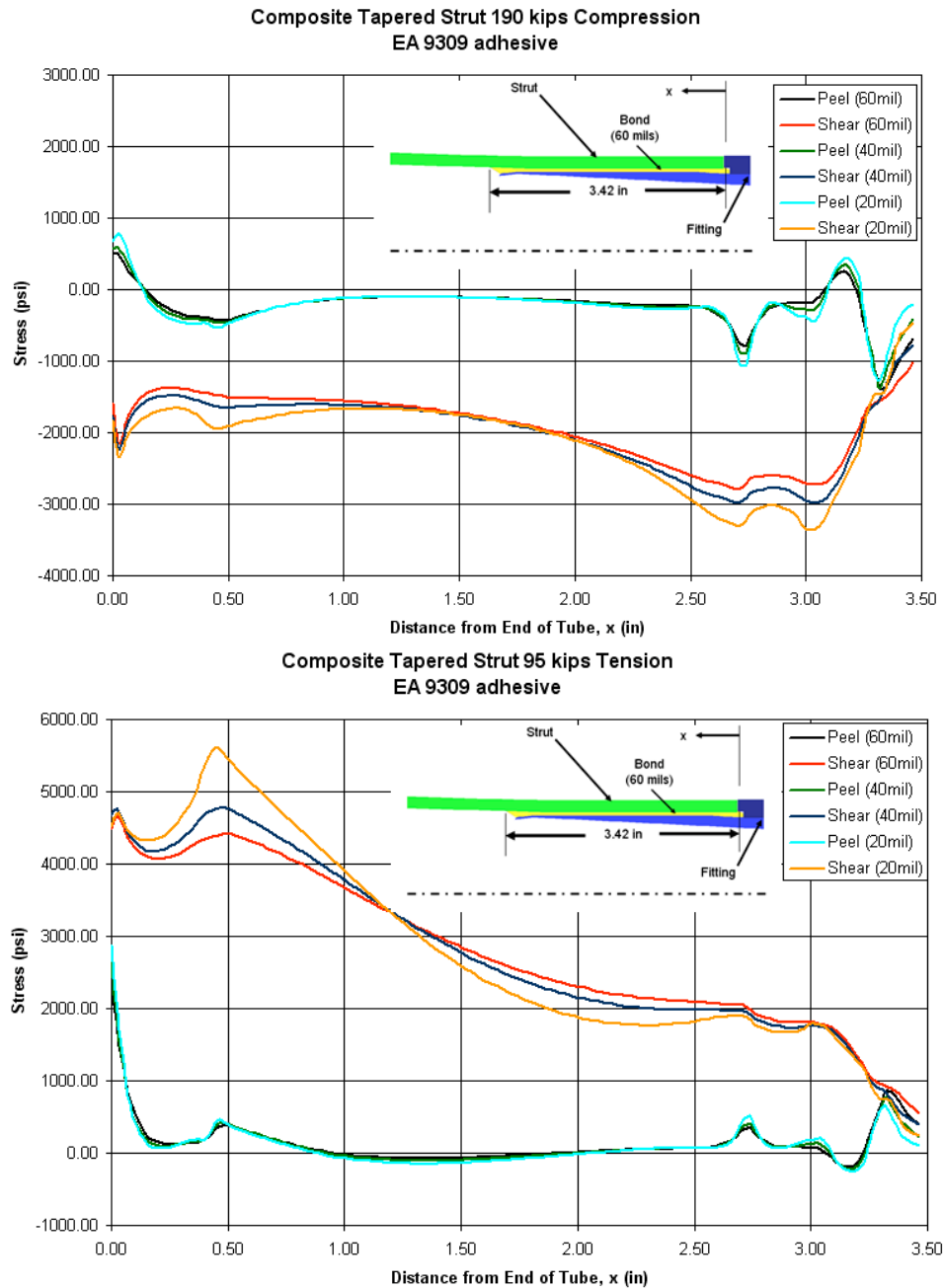
Comparing other high compressive modulus fibers showed that M55J is one of the best because of its high compression and interlaminar (IL) shear strength. Only M60J showed comparable properties. M55J/954-3 was chosen due to extensive in-house experience and materials database history.

Typical Mechanical Properties (Various Fibers)

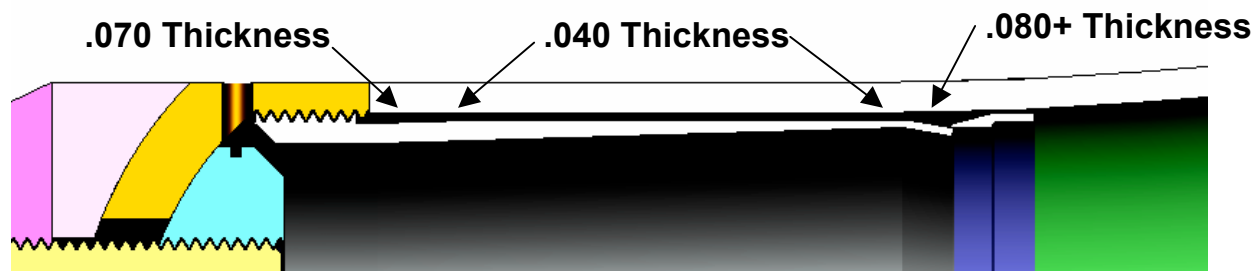
Property	Fibers (Average Values)					
	G80-600	M55J	M60J	YSH-60A	K13C-2U	K1100
0 Tensile Strength, ksi MPa	323 2227	334 2303	312 2151	332 2289	267 1841	190 1310
0 Tensile Modulus, Msi GPa	44 303	47 324	53 365	57 391	78 538	82 565
90 Tensile Strength, ksi MPa	5.7 39	5.0 35	— —	4.7 32	3.0 20	— —
90 Tensile Modulus, Msi GPa	0.80 5.5	0.90 6.2	— —	5.6 38	0.73 5.1	— —
0 Comp. Strength, ksi MPa	131 903	138 951	134 924	69 476	53 366	39 269
0 Comp. Modulus, Msi GPa	43 296	44 306	50 343	49 335	76 525	82 565
0 IL Shear Strength, ksi MPa	10.5 72	11.6 80	11.3 78	9.4 65	6.9 47	3.4 23

2.1.6 Bondline Thickness Evaluation

The effect of EA9309 bondline thickness, ranging from 20 to 60 mils, on the bondline peel and shear stress for both compressive and tensile loading was investigated. The results are presented below:



A reduction in stresses is observed with increasing bondline thickness. However, as the bondline thickness increases the bondline allowable decreases. Testing is required to determine the optimum bondline thickness at which the adhesive strength equals the composite strength.

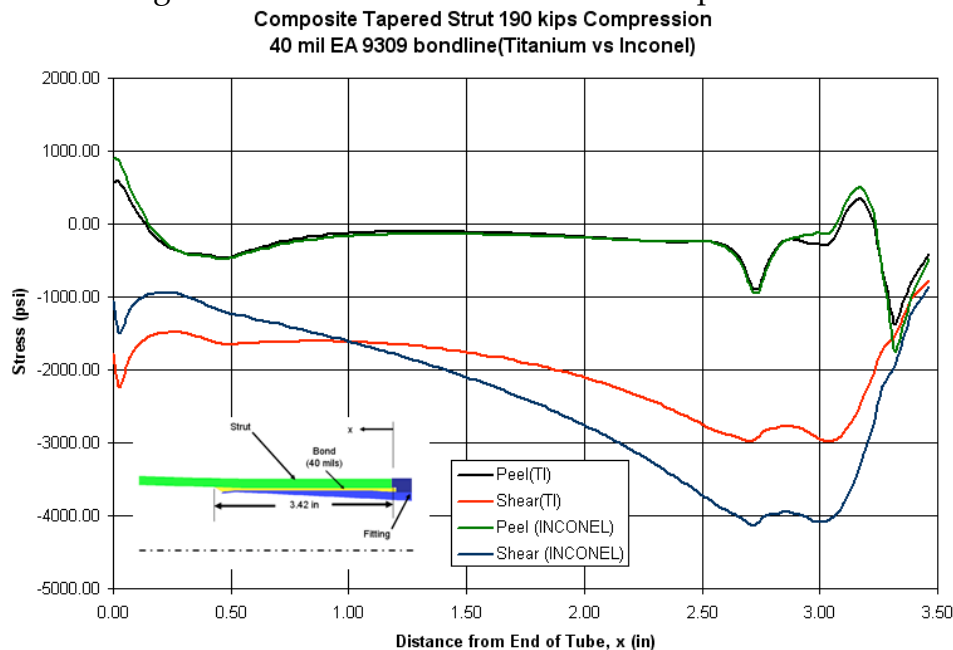


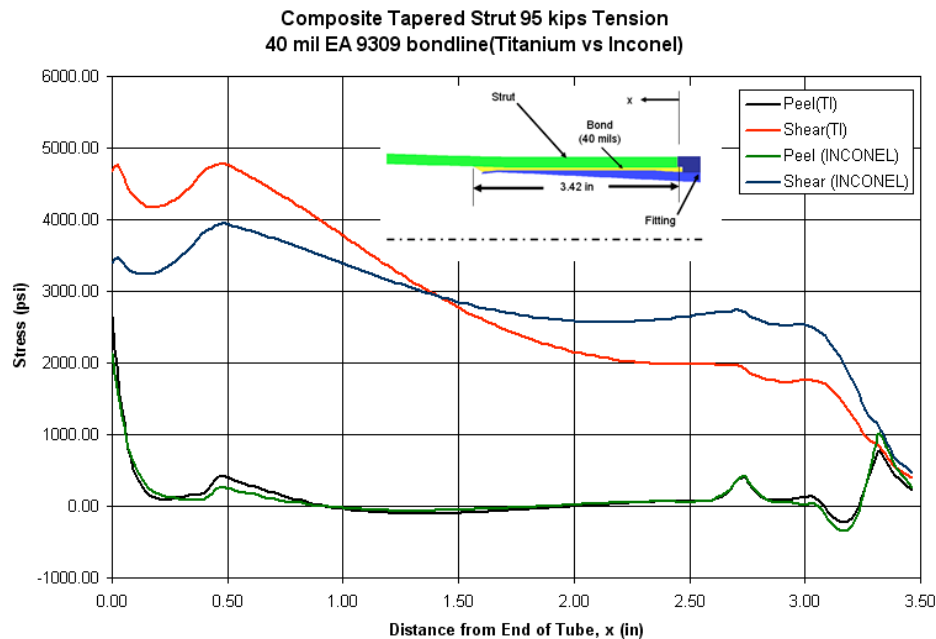
End Fitting Internal Fitting sculpted bond line thickness

The baseline EA9309 bondline thickness chosen for final analysis was a constant 40 mils thickness in the center zone with a tapering increase to 80 mils at the tip and 70 mils at the base. In addition, at the butt joint end, the design allows for the incorporation of a fillet bead of EA9309 adhesive to additionally relieve peak bondline stresses at this location.

2.1.7 Fitting Stiffness Evaluation

Another investigation was preformed to determine the effect of increasing the stiffness of the fitting on bondline stresses. The results are presented below:



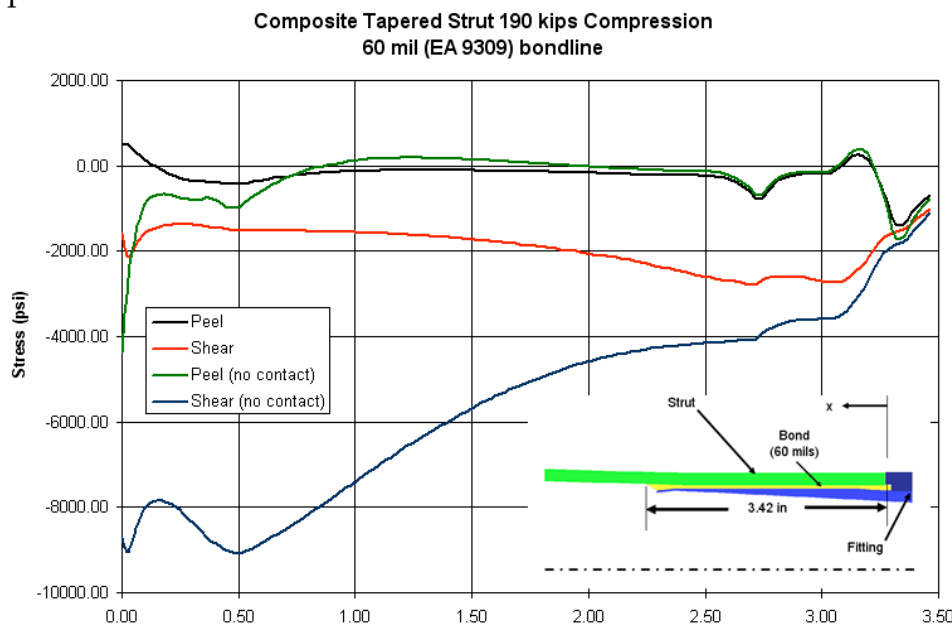


Implementing inconel, a higher modulus of elasticity material for the end fitting, created a stiffer end fitting which slightly increased the adhesive peel but greatly reduced the shear stress for compressive loading at the critical peak loading point, $x=0$. For tensile loading, a stiffer end fitting decreased both the adhesive peel and shear stress at the critical peak loading point, $x=0$.

The stiffer end fitting showed a reduction in bondline stress levels but came at the expense of doubling the end fitting weight. This study determined that a stiffer fitting was not overall beneficial towards a weight optimized system.

2.1.8 Fitting Contact Evaluation

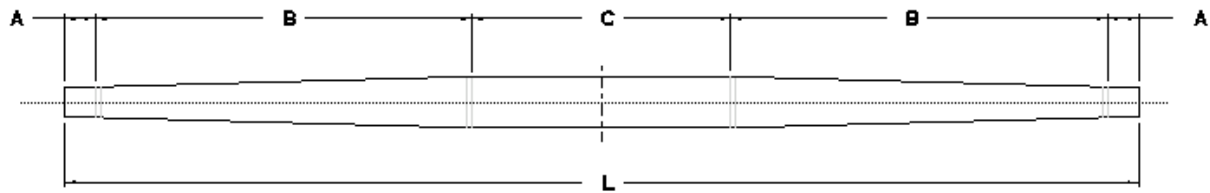
A comparison of bondline stresses for our fitting which makes contact with the strut at the butt joint versus the tradition approach of all loads going thru the adhesive interface in compressive loading was investigated for a 60 mil bondline. The results are presented below:



Results of the analysis indicate that 66% of the load is transferred through the fitting at the fitting/strut contact butt joint. This results in a 76% reduction in the maximum bondline shear stress.

2.1.9 Composite vs. Aluminum Strut Evaluation

For the ultimate load case of 190,000 lbs, the optimum M55J/954-3 tapered strut design has a 32 ply lay-up ($\pm 45^\circ/0^\circ_g/\pm 45^\circ/0^\circ_s$)_{SYM} with the 0° uni-directional ply thickness of 0.005 in and $\pm 45^\circ$ fabric of 0.010 in. This optimum design includes both stress and manufacturing requirements. Results of the analysis indicate that a weight saving of 61% was achieved over an aluminum truss of constant diameter having the same overall length. This weight savings can be attributed to the composite strut having 3.4 times the axial stiffness of an aluminum strut with 55% of the density. The results of this study are presented below:



Material	Tube Max Mean Dia (in)	Tube Min Mean Dia (in)	Tube Length A (in)	Tube Length B (in)	Tube Length C (in)	Thickness (in)	E_{axial} (Msi)	Weight (lbs)
M55J	5.43	3.18	3.42	41.31	28.54	0.18	34.51	17.69
Al	8.02	8.02	0	0	118	0.15	10.0	44.43

2.1.10 Structural Optimization Approach

A preliminary optimization code was developed with Mathcad. This was replaced with a more robust optimization code developed by Vanderplaats Research & Development called VisualScript and VisualDOC. VisualScript and VisualDOC were used to interface with a fortran code for structural analysis of tapered struts to determine weight optimized dimensions.

VisualScript is a GUI based set up of the optimization tasks for VisualDOC. It interfaced directly with the fortran input, output and executable files. VisualDOC is also GUI based. It provides gradient, non-gradient and response surface based optimization algorithms along with design of experiments. VisualDOC can be used for any design problem since you direct VisualDOC by defining what parameters may change (design variables) and measures of design quality (responses). VisualScript and VisualDOC are very effective tools for GUI optimization.

2.1.11 Structural Analysis Summary

A tapered strut weight optimization code was developed to design the strut to the load requirements. The end fitting diameters were determined based on a system of node, end fitting, and strut loading requirements with specific considerations from SD Composites for the manufacturing processes. An ABAQUS axisymmetric FEM was developed to determine the design of the bonded titanium end fitting. A unique load biased end fitting was invented that takes the majority of the compression loads in bearing thru a butt joint but takes 100% of tension loads thru the bondline. The bondline loads peaked in the derived tension case. Several investigations were undertaken to mitigate this peaking load. By varying the bondline thickness and by selecting the appropriate adhesive, we successfully reduced the peaking load. Our analysis shows a positive margin of safety for the weight optimized tapered strut. Its primary failure mode is column buckling. In depth studies of the secondary failure modes, crippling and first ply failures at the end fitting bonded joint interfaces also showed positive margins of safety. Due to the inherent nature of a process sensitive bonded joint system, the only way to verify the crippling and first ply allowables is thru testing. Once we complete the proposed subscale testing outlined in Section 2.1.12, we will be ready for full scale build and test of the tapered strut, end fitting, and node system.

2.1.12 Proposed Subscale Testing

It is proposed that a series of subscale tests be run to determine the bondline and strut capabilities. Since the tensile loading results in the greatest bondline stresses, this loading condition will be used to determine bondline capability. On the other hand, the compression loading will be used to determine the strut crippling capability.

A constant 3 inch diameter strut will be manufactured of M55J/954-3 with a 32 ply lay-up ($\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ_5$)_{SYM}. It will be cut into several twelve inch length sections. Each section will have fittings bonded onto either end. The struts will be placed in a tensile/compression testing machine that is enclosed in a thermal chamber. Multiple tension & compression tests will be run at hot (+250°F) and cold (-150°F) temperatures. The fitting design will be modified until the ultimate tensile & compressive loading conditions are met. This subscale testing effort will confirm our previously derived material database and assumptions used in our analysis. The uncertainty in bondline allowables due to scatter in the flatwise tension and interlaminar shear strength allowables can only be resolved through testing. Our low cost test process will take about 4-6 weeks to complete and the results will give us total confidence of success in the manufacturing the full scale tapered strut.

2.1.13 Proposed Full Scale Testing

It is proposed that a series of full scale tests be run to determine the system level capabilities. Case 2 (ultimate load case of 190,000 lbs) will be tested as it is the "tall pole" strut that has the highest compression load. The test structure will consist of a

127 inch long tapered strut made of M55J/954-3 having a 32 ply lay-up ($\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ$)_{SYM} with end fittings, and attach nodes. Three tension & compression ultimate load level tests will be run at hot (+250°F) and cold (-150°F) temperatures in a node-to-node flight configuration.

2.2 Manufacturing Demonstration Article

The manufacturing of the demonstration article was successfully performed by San Diego Composites (SDC). Their expertise in manufacturing as well as providing a unique and effective process was critical for accomplishing this activity on time and within budget. SDC considered several manufacturing methods for the tapered composite strut – including alternatives for the layup and cure of the part. For the layup: hand layup, filament winding, tape placement, and pultrusion were considered. For curing: autoclave, matched metal tooling, and bladder molding were considered. Based on results from the trade studies performed at LMSSC, several methods were eliminated from consideration. For example:

- Pultrusion was eliminated because it is typically used for constant cross section parts and the purpose of this strut is to have a varying cross section
- Interior hard tooling for the part is also not desirable due to the trapped nature of a tapered part and therefore would require high complexity to remove and high expense to manufacture
- Filament winding was removed from consideration because of potential manufacturing challenges due to the tapered geometry and a high percentage of low angle fibers in the layup

In the end, SDC determined cast bladder molding to be the best manufacturing method. The SDC cast bladder manufacturing process is a multi-step method that was specifically designed to allow for composite structures with largely trapped features to be reliably tooled and easily removed from the completed and cured part. This is done by providing multiple tooling elements that can be broken down and removed at different stages in the construction. The key components are: 1) a washout wax mandrel, 2) inflatable/collapsible silicone bladder molding, 3) aluminum mandrel backbone, and 4) the outer mold.

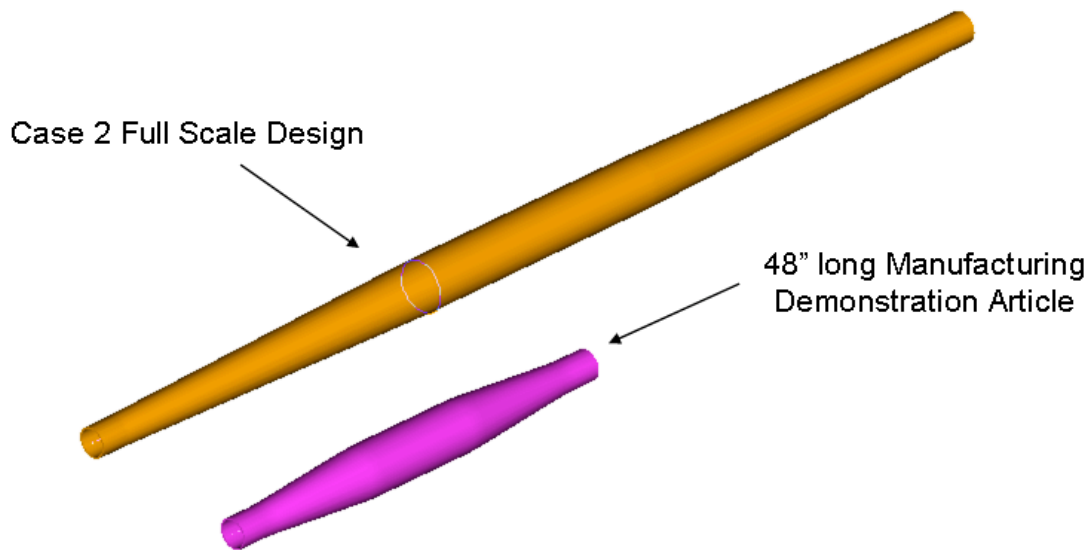
Hand layup was selected for composite placement method due to the single build quantity. It should be noted that automated tape placement may show an advantage as a production manufacturing process due to potential labor cost savings. Should production parts be manufactured with tape placement, none of the manufacturing achievements made in this effort would be invalidated. The method of composite lay-down is a minor player in the manufacturing process demonstrated in this study.

2.2.1 Manufacturing Demonstration Article Design

The most challenging aspect of manufacturing a composite tapered strut of the Case 1 or Case 2 designs is providing a process solution that allows for trapped tooling to be removed upon completion of the composite cure cycle. Proof of tool removal was

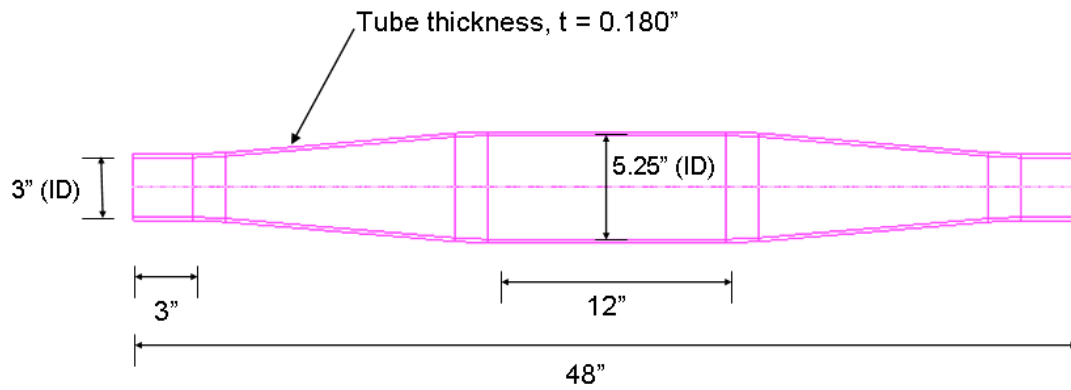
deemed to be the main charter of the manufacturing demonstration article by the LMSSC/SDC team. Towards that end, there were two modifications made to the manufacturing article design from the flight hardware design that did not affect this end goal but did allow for efficient technology development.

First, the overall length of the tube structure was reduced from 118" to 48". The primary motivation behind this change was to minimize the cost and schedule impact of the tooling.



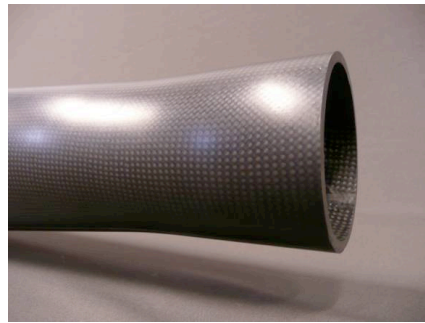
Second, the manufacturing demonstration article was constructed of GRAFIL 34-700/NB301 material instead of the M55J/954-3 flight prescription. Material selection for the manufacturing demonstration article is rather inconsequential – so long as the cure process between the demonstration composites system is similar to the flight material. GRAFIL 34-700/NB301 is a high strength, standard modulus, PAN based carbon fiber with a 300°F cure epoxy resin system. M55J/954-3 is a high modulus, standard strength, pitch based carbon fiber with a 350°F cure cyanate ester resin system. The selection of GRAFIL 34-700/NB301 over M55J/954-3 or other similar curing products was mainly due to its immediate availability – thereby providing cost and schedule efficiency.

All other elements of the Case 2 design were maintained as they were thought to be critical in exhibiting this proposed manufacturing process. Specifically, all cross sectional dimensions (thickness, Max ID, and Min ID) of the manufacturing demonstration article are identical to the full-scale flight design.



2.2.2 Completed Manufacturing Demonstration Article

The SDC cast bladder manufacturing process produced a successful part on the first attempt.



Dimensional inspection showed exceptional compliance to the design dimensions for a first article build. Measurements of the completed parts highlighted several areas where manufacturing assumptions would be refined on future builds.

	Units	Design	Measured	
			Average	Range
Mass	lb	6.94	6.91	-
Max OD	in	5.610	5.598	5.595 - 5.600
Min OD	in	3.360	3.354	3.353 - 3.354
Min ID	in	3.000	2.993	2.980 - 3.005
thickness	in	0.180	0.181	0.166 - 0.196
length	in	48.000	48.00	-

First, all outer dimension measurements are slightly smaller than the nominal design dimensions. This is because the schedule forced design and procurement of the outer mold tool prior to final selection of a material and the tooling scale factor was computed for a 300°F cure (whereas the actual cure was performed at 275°F). Tooling scale factor would be a non-issue for production parts as the material would be selected far in advance of tooling design and procurement

Second, the thickness range is a direct product of the tooling used to position the internal mandrel relative to the outer mold. Dimensional inspection shows that the thickness ranges from 0.166 to 0.196 as you move across the circumference of the tapered strut. In other words, the resulting thickness variance is a result of an overall offset between the mandrel and the outer mold. This merely shows that the positional tolerance between the mandrel needs tighter tooling than prescribed for the manufacturing demonstration article.

Lastly, the surface of the tapered strut exhibits minor aesthetic (non-structural) irregularities. Based upon past experience at SDC, a higher pressure during the part cure is expected to remove this feature.

Also, it should be noted that the delivered hardware is out of the mold quality. No attempts have been made to improve aesthetic features by abrading resin rich areas along the outer mold seam or areas on the internal surface. Several abrasion techniques could be used to remove these features if so desired by the end use customer.

2.2.3 Manufacturing Demonstration Lessons Learned

In general, the team is pleased with results from the first manufacturing demonstration article. Nonetheless, three areas have been identified for process improvements to yield better parts on future builds.

1. The internal surface of strut could be improved with process modifications to yield better silicone surface

The visible seams on the internal surface are due to the patchwork mold used for the silicone bladder on the manufacturing demonstration article. In a production sense, a separate tool would be utilized to form the silicone bladder – thereby removing the surface roughness entirely.

The dimples of resin rich areas on the internal surface are a result of small voids in the silicone bladder. These voids are a result of entrapped air during mixing of the

silicone. For all future builds, SDC plans to provide a degassing step to the silicone after mixing and prior to placement.

2. The outer surface aesthetics of the strut can be improved

The non-structural surface irregularities on the outer surface are attributable to lower than anticipated resin flow. Higher pressure during cure would force excess resin to occupy all surface features on the outer mold. SDC plans to incorporate this lesson on future cures.

3. Thickness range can be better controlled

Dimensional inspection showed a circumferential trend to the varying thickness (i.e. offset circles for the IML and OML of the parts). This highlights the need to hold higher tolerancing on parts used to position mandrel in the outer mold. Future tooling design will incorporate better positional tooling between these components.

2.2.4 SDC Bladder Casting Process Advantages over Washable Technologies

The LMSSC/SDC team intentionally avoided the use of more typical washable tooling technologies for this application. This was done for a number of reasons that will provide significant advantages during the production stages.

First, bladder casting utilizes reusable tooling. For multiple builds of the same design, this will provide lower cost and shorter schedule times between builds. In bladder casting, the outer mold, the silicone bladder, and paraffin wax are all reusable; whereas, washable mandrels require forming and machining for every build.

Second, part quality is extremely consistent using bladder casting because the outer mold provides a tooled surface during the cure. This, in turn, will reduce scrap and part rework rates. Washable mandrel parts will exhibit build to build differences due to the workmanship necessary in bagging a cylindrical part like the tapered strut.

Third, bladder casting is an out-of-autoclave process. The internal pressure (bladder) cure provides high quality compaction without the need to dedicate an autoclave resource. The avoidance of autoclave time is certain to reduce manufacturing production costs.

Lastly, bladder molding provides no risk of “unwashable” remnants internal to the strut. The bladder provides an impenetrable surface for the resin during the cure where washable mandrels often crack and allow resin to infiltrate mold material. This is thought to be the highest risk for washable mandrel technologies used on the tapered strut applications. The small diameters and long lengths provide virtually no means of chipping away internal unwashed mold material.

2.2.5 Follow-on Production Manufacturing Assessment

It is anticipated that the configurations studied in this activity would ultimately be part of a larger structural system assembly, for Altair and/or other Constellation architectures. However, we also recognize that several additional strut configurations

would be required to complete the entire structure. As such, we have designed this node-to-node system to be readily scaleable for use in that type of application.

For a basis of comparison, we have established a Rough Order of Magnitude (ROM) cost and schedule for a single run production build effort.

Assumptions used are: 4 unique strut configurations; 1 tooling set per configuration; 25 struts per configuration, for a total of 100 struts; utilize existing production capacity; hand lay-up.

Given those assumptions, we estimate that we could produce one of each configuration per week, for a total time of six months at a cost of \$2 million (\$20k per strut). As stated, this estimate is provided for use in as an order of magnitude comparison to other alternatives that may exist.

3.0 PROGRAM SCHEDULE

The manufacturing task was performed in a three month period and was successfully executed accordingly to schedule.

4.0 DELIVERABLES OF THE MANUFACTURING TASK EFFORT

Our team has successfully delivered the following contract requirements:

- 1) Informal biweekly progress reports
- 2) Optimum design of two struts meeting the requirements listed in Table 2-1
- 3) Final report including description of how optimization was accomplished, what parameters were considered and the manufacturing method that was used to build a subscale demonstration test article
- 4) Manufactured a demonstration one piece tapered strut

In addition, we investigated, designed, and analyzed the end fitting and node components that would be integrated into a tapered strut system. We made ABS plastic models of these components for visual reviews.

5.0 RELEVANT EXPERIENCE AND PAST PERFORMANCE

Lockheed Martin Corporation has designed, analyzed, and built many aerospace composite strut structures for NASA, DoD and Commercial Spacecraft missions (Figure 5-1). Among these are Magellan, Stardust, MRO, Phoenix, Milstar, Special Programs, X-33, Atlas, and Orion W-truss. These tubes have been made using T300, M55J and IM6 fibers in epoxy and cyanate ester matrix. They were constant diameter tubes with diameters ranging from 1-4 inches and have been extensively used in different spacecraft truss structures. Additionally, tapered composite tubes with single taper from 18 to 13 inches and 13 to 7 inches have been used in our military space programs. For the X-33 program, the development and manufacturing of IM-7/ 5250-4 composite truss tubes (2 in and 4 in constant diameter struts) was a collaborative effort between LM Aeronautics Skunk Works (NASA Cooperative Agreement NCC8-115.) and Space Systems Denver, performed under the NASA X-33 Single Stage to Orbit Demonstration Program.

6.0 PROJECT ORGANIZATION

The project organization is composed of a project lead and a technical lead, with support from mechanical designers, analysts, and manufacturing personnel.

The project leader is Mr. Jebediah Brewster, who has extensive experience in system engineering and program management. The technical leader is Dr. Mark Lajczok who has extensive composite analysis experience and is considered the LMSSC subject expert on composites and bonding.

7.0 SUMMARY

The project successfully designed and manufactured a very light weight one piece composite tapered strut that is fully representative of a full scale flight article. In addition, the team designed and built a prototype of the node and end fitting system that will effectively integrate and work with the full scale flight articles. This complete node-to-node system was optimized for weight and manufacturing efficiency. We demonstrated that the composite strut is just one integral part of the node-to-node system and the optimization of just the strut is not effective at reducing the total system weight.

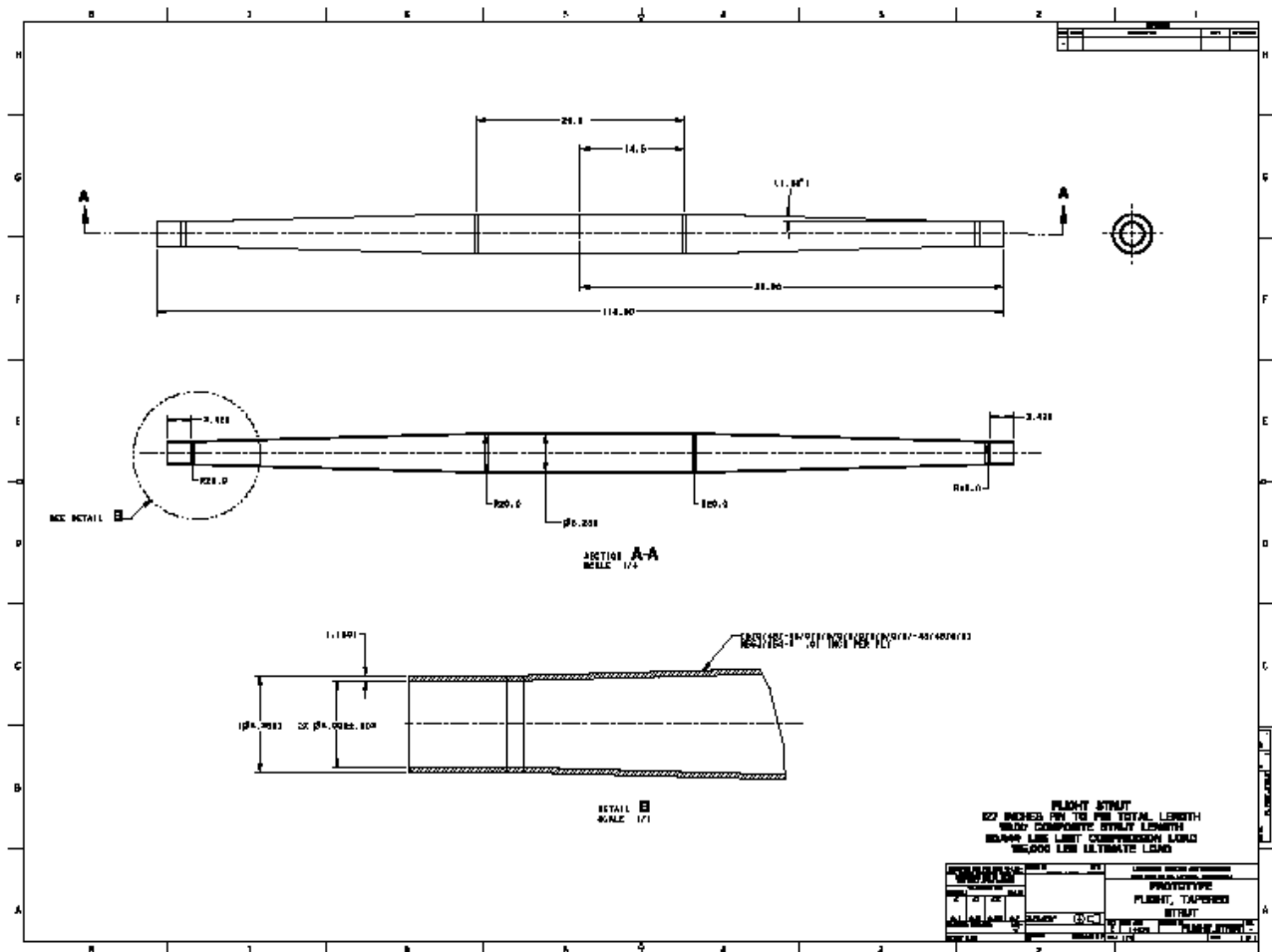
Our design solutions dramatically decreased the weight of a node, end fitting, and strut system over an aluminum based system while also significantly increasing the dynamic system stiffness.

8.0 APPENDIX

8.1 PDF Drawings

Manufacturing PDF drawing (note: 2 sheets)

Flight Tapered Strut Full Scale Drawing:



REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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